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Recycled Paper

DEVELOPMENT OF ELECTROSTATIC QUADRUPLES FOR HEAVY ION FUSION

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ABSTRACT

High-voltage electrostatic quadruples are used for focusing ion beams at low energies in the induction linac approach to heavy ion driven inertial confinement fusion for the production of electrical power. The transportable beam line charge density depends linearly on the operating voltage of the quadruples, so an experimental program was conducted to find the voltage breakdown dependence on the overall size of the quadruples which would then allow determination of the best geometry and operating voltage. The quadruple electrodes are usually stainless steel cylinders with hemispherical end caps, mounted on stainless steel end plates. The end plates are precisely positioned with respect to each other and the vacuum chamber with alumina insulators with shielded triple points.

It is advantageous for beam transport to employ an array of multiple beams for which a rather large number of interdigitated electrodes forms an array of quadrupoles. The trade-offs between very large numbers of small channels and a smaller number of large channels, and the dependence of the choice on the voltage breakdown dependence is discussed. With present understanding, the optimum is about 100 beamlets focused with quadruples which have a beam aperture radius of about 2.3 cm and are operated with about 150 kV between electrodes.

1. INTRODUCTION

Electrostatic quadruples have long been used in the transport and focusing of charged particle beams. In many cases the beam currents are low and the required quadruple voltages are low, so the problem becomes one of just finding a good field geometry. For heavy ion fusion, however, the beam currents and the operating voltages are high. In this approach to fusion the driver which heats the fusion capsule is a heavy ion accelerator which accelerates a few hundred microcoulombs of ions to energies of about 10 GeV which hit the target in about 10 ns [1]. Beam transport is a major issue, and the present-day scenarios favor electrostatic quadruple lenses at low energies and magnetic lenses at high energies. In this case the design includes considerations of voltage breakdown, the dependence of transportable current on various parameters, and the field quality. The design is most challenging at the lowest particle energies, where the required focusing period lengths are short and the axial space required for voltage standoff and the end plates is a significant fraction of the total. (The focusing lattice half period, or one quadruple and its adjacent drift space would be -20-25 cm long for a beam aperture radius of~2.3 cm; a smaller aperture leads to higher gradients and even shorter half-periods). At higher energies the quadruples can become longer, easing the packing constraints. At very high energies, a hundred MeV and above for heavy ions, magnetic quadruples are generally preferred because they are stronger (in most circumstances), although designs using electrostatic focusing can be made to work throughout the entire accelerator.

For the heavy ion fusion application the basic goal is to accelerate the largest total line charge density through a given aperture. (An earlier paper on electrostatic quadruples emphasized beam transport considerations[2].) This can be achieved with either a few large diameter channels or a large number of small diameter channels. The focusing of charged particle beams by electric quadruples essentially depends on the gradients of the transverse electric field, dE/dx and dE/ dy, for particle motion in the z direction. It is well known that the highest fields can be attained over the smallest distances, in which case the gradient of these fields gets very large, being proportional to E_{max}/a or V/a^2, where E_{max} is the field limit at an electrode surface, a is the quadruple aperture radius, and V is the potential difference between adjacent electrodes. What these field and voltage limits are and how they depend on geometry and other factors is a principal issue determining channel size. The optimum lattice from such considerations is clearly a very large number of very small beams. Designs utilizing well in excess of 1000 small (a few mm radius) beams have been seriously advocated [3] and may indeed be the ultimate choice. At this time, however, other considerations related to the cost of manufacture of small precision parts, their assembly into the focusing arrays, and the accurate alignment of many such arrays into a long beam transport line lead to an uncertainty in the beam centering which requires a clearance between the beam and the vacuum chamber, and this moves the optimum number of beams down toward 100 and the dimensions of the apertures and electrodes up to the cm range. A representative array for four beam channels is shown in Fig. 1. It was designed for the Elise Accelerator [4] and is similar to what would be used in high power heavy ion accelerators except that the number of beams would be considerably greater.

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2. RESULTS FROM THE BREAKDOWN EXPERIMENTS

There is reasonably well known and consistent data for breakdown between parallel metallic planes in vacuum, and between planes and spheres. However, it is much more difficult to find breakdown data for multipole fields, such as occur in an electrostatic quadruple. A plot of the electrostatic fields and potentials in a two-dimensional approximation is shown in Fig.2.

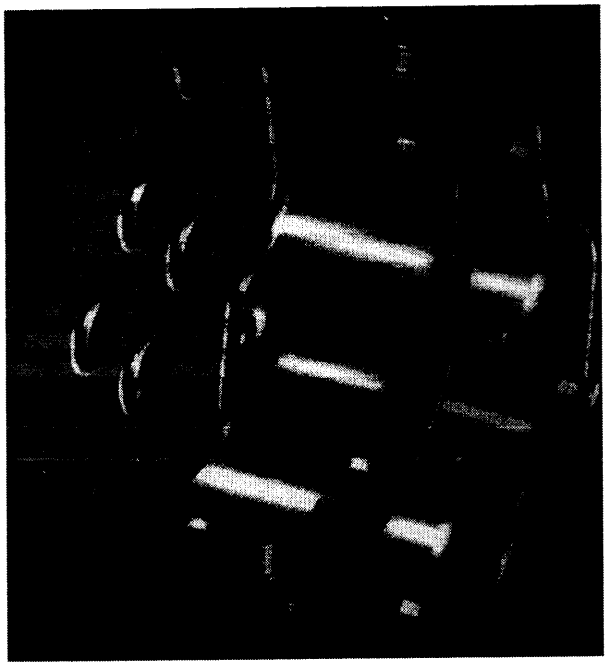


Figure 1: A CAD drawing of a four-beam electrostatic array, designed for the Elise accelerator.

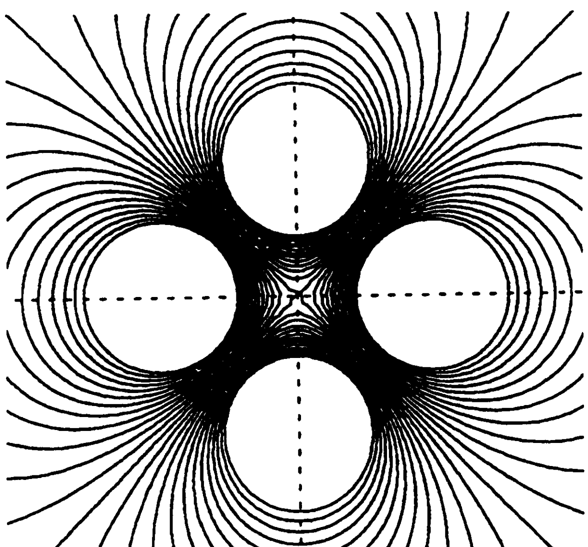


Figure 2: Electrostatic potential contours in an array using cylindrical electrodes. This is a 2D approximation using the Poisson computer code.

Most probably, for the geometry of interest, the breakdown is in the high field area away from the quadrupolar region, where the field is essentially the field distribution between two parallel cylinders. For beam dynamics purposes the full three-dimensional fields are also computed and used. We have found little dependence of the breakdown on the details of the electrode ends, contrary to what might be expected, with end caps which have a radius equal to the radius of the electrode and half that radius showing no difference. From this we infer that the voltage limits are largely determined by the 2-D fields between the cylinders.

Using the parallel plane breakdown data as a first approximation to the voltage holding between the cylinders, we tentatively expected the breakdown voltage to be linear with spacing for the first centimeter and then to merge into a square root dependence of voltage versus distance as the spacing is increased. As will be shown later, the desired operating region falls directly in the transitional region between the linear and square root dependence.

To investigate the actual breakdown dependence, we constructed several single channel quadruples which bracketed the region of interest. In the initial series of these tests (in 1984) we mounted the quadruple electrodes on two parallel plates which were insulated from each other and supported by very long outboard insulators which were longer than the quadruples. For the purpose of seeking the breakdown voltage between electrodes, the insulators can be made better than required, by moving them away from the working region, and elongating them.

However, in a realistic multiple beam array for the fusion application there also is an economic incentive to make the array compact due to the cost and proximity of the induction cores used for accelerating the beams. The insulators could be subdivided and moved further from the array of electrodes. In this sense, we view the breakdown between electrodes to be a fundamental limit, and consider that the insulators can be made to fit.

In the present series of tests, several insulator designs were tried, and this work is continuing at the present time, with the goal of determining how close to the electrodes it is possible to place the insulators. The present insulators span the space directly between the parallel plates, as shown in Fig.3.

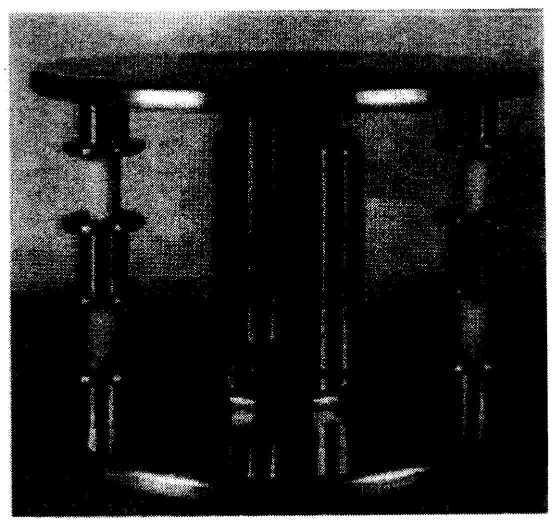


Figure 3: Quadruple focusing element that was used for the test results of Fig. 4.

We also continue to consider angled insulators, which increase the available insulator length and are mechanically sturdier.

The quadruple geometry which is usually chosen and to which everything in this paper refers, the so called "ideal geometry", has an electrode radius which is 1.146 times the aperture radius. For practical purposes this is a ratio of 8 to 7. This geometry has the property that the next higher allowed multipole in a field expansion vanishes. Taking into account the four-fold symmetry of the electrode geometry and the voltage distribution on it, this multipole is the dodecapole or 12-pole. The multipole after that, the 20-pole, and all the higher multiples, are non-vanishing, but they have a rapid decrease of field going toward the center (as r $e^{[n/2-1]}$, where n is the multipole number), with the result that the field errors are appreciable only near the electrodes. The field is very good or almost pure quadrupolar at smaller radii, where the beam is located. With this geometry, for operating voltage and breakdown purposes the field can be considered to be pure quadrupolar within the beam aperture, and for beam dynamics purposes it is almost perfect. Because the highest fields occur well away from the beam aperture, between the adjacent electrodes, beam impact is expected to have a minor influence on voltage breakdown.

The transportable average charge density, in microcoulombs per cubic meter of the quadrupde array, is the line charge density, lambda, divided by the square of the channel spacing or pitch, p. It depends on the field gradient as

$$\langle\lambda\rangle = \lambda/p^2 \propto \frac{Ea_b^2}{p^2} = \frac{\left(\frac{E}{a}\right)\left(\frac{a-\delta}{m}\right)^2}{(ka)^2} \qquad \text{(EQ 1)}$$

where: E is the electric field at the aperture radius, a; E' is the gradient of the field, δ is a clearance between the beam and the aperture, and m is a factor near one; and k is a proportionality factor relating a to p. Neither of these multiplicative factors (m, k) nor others which have been omitted here affect the determination of the optimum. Only the functional form of the voltage breakdown and the clearance δ affect the result. For an algebraic dependence of maximum fields given by

$$E = E_o\left(\frac{a}{a_0}\right)^l$$

$$\langle\lambda\rangle = \left(\frac{a^l}{a}\right)\frac{(a-\delta)^2}{a^2} = (a^{l-3})(a-\delta)^2 \qquad \text{(EQ 2)}$$

has a maximum at

$$a = \left(\frac{l-3}{l-1}\right)\delta \qquad \text{(EQ 3)}$$

The $V \propto d$ relation is for a constant field, for which l=0, and gives a=3δ.

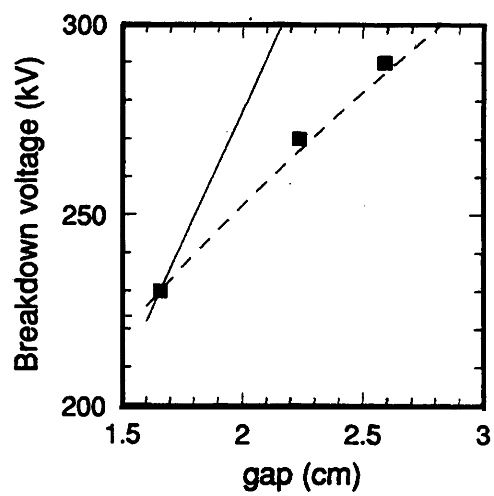
The $V \propto d^{1/2}$ relation has l=-1/2 and gives a=2.33δ.

Infrequently a constant V with distance is claimed, for which l=-1, and a=2δ.

Our measurements, shown in Fig. 4, strongly suggest the square root dependence and give the a=2.33δ result. Other calculations indicate that a clearance of about 1 cm is required in a long transport line with present day accelerator alignment technology.

At a more refined level of calculation, the transportable charge depends not on the experimentally measured points being well fitted by the V being proportional to the square root of d, or some other power, but to the value of the field and its derivative near the operating point, or some closer approximation to the real data. Such refinements move the optimum by a small amount. On the other hand, smaller beam apertures, contingent on improved fabrication and alignment tolerances in the future are the direction towards which we would like to proceed. Because of such considerations, and because of the uncertainties in the present measurements, we have chosen a 2.3 cm radius aperture as the present optimum.

The surface treatment for the various components corresponds to that for good vacuum practice for accelerators. That is, it is not quite as good as required for ultra-high vacuum used in surface physics experiments. For this reason, vacuum breakdown data collected in earlier decades such as the 1960's -- when the surfaces were not as clean and the vacuums as high as in research apparatus today -- are very relevant. Also, improvements due to super fine polishes are not considered relevant, because after voltage conditioning, the surfaces have new small craters and the insulators show slight discoloration. We try to limit the readily accessible electrostatic energy in the high voltage region to less than 10 joules by isolating the power supply and its output cable energy through the use of very high resistance cable, and by using short, back-terminated cables between the quads and external capacitors whose purpose is to decrease the voltage change of the quads caused by the beam within them.



pendence becomes noticeably square root.

3. OTHER CONSIDERATIONS IN THE DESIGN OF AN ACCELERATOR WITH A LARGE NUMBER OF ELECTROSTATIC QUADRUPLES

While not as fundamentally important as the breakdown dependence between electrodes, the HV vacuum feed-through and the standoff insulators are major
9 elements of the complete quadruple design. In both instances the designs we favor have stress reducing metal conical shields in the region of the negative triple point. The insulators and the shields, as shown in Fig.3, have, when isolated, withstood approximately 300 kV. In the assembled structure all of these elements work together, and we have not tried to determine the relative contributions of each. As expected, the array holds less voltage than the component parts. But as noted previously, we consider the electrode-to-electrode breakdown as the fundamental limit, and are concentrating on insulator and feedthrough details as the probable weak links. Further improvements will come from relatively minor changes, such as in electrode and insulator material selection and cleaning procedures, bake-out, polishing, etc.

Throughout our development we have tried to attain a safety factor of approximately two between the breakdown voltage and the operating voltage. Some appreciable safety factor is needed for several reasons:

a) The tests are all done with single quadruples in a laboratory environment and over a period of a few days, the completed accelerator will have to operate for years with little attention to individual components;

b) We expect variations among the channels in the array, corresponding to surface contaminants, bums, etc.;

c) We expect variations along the accelerator from array to array;

d) We expect occasional vacuum failures during which the quadruples could get contaminated; and

e) There will be a small radiation background from the secondary electrons produced by beam impact over and above that due to the dark current of the quadruples themselves.

The operating voltage of the focusing system is limited to the lowest value of the entire distribution of breakdown voltages for the approximately 500 arrays which would be **used** in a full driver. In the two previous electric quadruple focused beam transport experiments at LBNL, SBTE using 87 quadruples of 2.54 cm aperture radius and MBE-4 using 68 quadruples of 2.7 cm radius, the operation was generally satisfactory: SBTE operated with about 15 kV between electrodes and had no voltage breakdown problems [5]; MBE-4 operated at up to 80 kV between electrodes and had a few vacuum HV feed-through problems[6]. The optimum we are searching for here is for a smaller aperture and almost twice the previous highest operating voltage. In a future high current beam transport experiment with these new quadrupoles we will explore the actual maximum operating voltage and the minimum beam to electrode clearances, both of which have the potential to substantially increase the transportable charge.

4. ACKNOWLEDGEMENTS

This work builds upon the previous experiments performed with Dr. Stephen S. Rosenblum and computations performed by Victor Brady and others.

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